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Uncertainties in Measurements and Calculations of Nonelastic Cross Sections

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Scatter in presently available measurements of the nonelastic cross section indicates that this quantity is rather poorly known (approximately 5-10%). We will show examples of this, together with results from a new technique that shows promise of reducing these uncertainties to ≈2-3% in the range of a few MeV to a few tens of MeV. Comparison of results obtained using this new technique with optical model calculations suggests that global optical potentials are not reliable for predicting nonelastic cross sections to better than roughly 5%. In view of these results, we suggest that a limited set of high-precision measurements should be made to clarify the experimental picture and guide the further development of optical models.

I. INTRODUCTION

The nonelastic cross section for incident neutrons is an important quantity because it represents the sum of all reaction processes that can occur except for elastic scattering. In particular, this quantity yields the compound-nuclear formation cross section that is the first step in a Hauser-Feshbach or Weisskopf-Ewing reaction calculation, if compound elastic and direct-inelastic processes are properly accounted for. In some cases, such as in the interpretation of experiments using the surrogate-reaction technique to measure cross sections on unstable targets, the compound formation cross section must be supplied with sufficient accuracy by an optical model calculation. Examples of recent applications of this technique to the measurement of fission cross sections can be found in Refs. [1],[2], and [3].

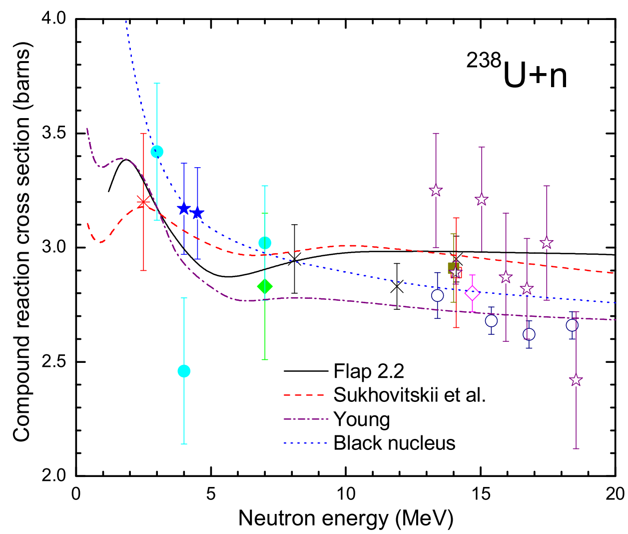

FIG. 2: Same as Fig. 1, with three optical-model predictions as well as that of a simple black-nucleus model; see text.

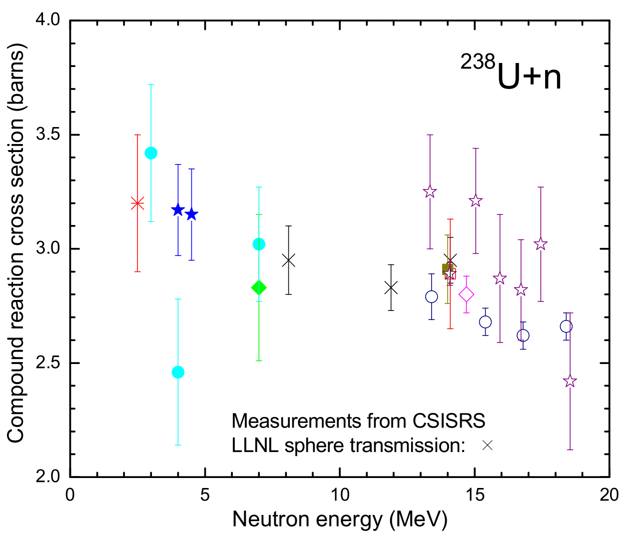

FIG. 1: Measured compound formation cross sections for ^{238}U taken from the CSISRS database. Points near 8, 12, and 14 MeV from [4] are indicated by crosses.

In spite of their importance both for direct application and for the development of optical models, nonelastic cross sections are rather poorly known, usually to no better than 5-10% accuracy. It is the purpose of this paper to show the limitations of our present knowledge and to suggest how the situation can be improved. Although the problems are evident over the entire periodic table, we will illustrate these problems using iron and actinide nuclei.

Fig. 1 shows the present state of measurements on ^{238}U, as taken from the CSISRS database. These measurements are actually for the compound reaction formation cross section rather than the nonelastic cross section, since the experimental technique excludes the most important direct inelastic excitations (the first few levels of the ground-state band). Clearly the cross section is not well determined by the measurements; the data spread by about ±10% and in some energy regions the data are discrepant by amounts that significantly exceed the error bars.

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In view of the discrepancies in the measurements, it might be hoped that optical potentials that have been determined from other data (mainly total and differential elastic cross sections) might agree on their predictions of the the compound formation cross section. This is not the case, as illustrated by the results plotted in Fig. 2 for a sample of three coupled-channels optical potentials, along with a simple black-nucleus estimate. There is still a 10% spread in these predictions, which persists across the entire energy range shown. The optical potentials are from Refs. [5], which has been used in analysis of Livermore surrogate-reaction experiments; [6], a recent potential fitted to both neutron and proton data; and [7], a neutron potential developed at Los Alamos. The black-nucleus estimate is simply $\pi(R + \lambda\!\!\!^{-})^2$, where R is chosen as $1.38A^{1/3}$ fm; the direct inelastic excitations calculated with [5] were subtracted from this value. Unfortunately, the potentials do not guide the choice of which experimental data are reliable, and the data do not definitively choose among the optical potentials. Even the obviously oversimplified black-nucleus estimate compares with the data about as well as optical potential results.

II. SPHERE TRANSMISSION MEASUREMENTS

Nearly all direct measurements of nonelastic cross section have been made with the sphere-transmission technique, illustrated in Fig. 3. For an ideal experiment (point detector and very thin spherical shell of sample material surrounding the detector), the flux heading directly toward the detector that is removed by elastic scattering is exactly compensated by elastic inscattering from the full spherical shell. If the detector is insensitive to the debris from true nonelastic events (normally achieved by having a sufficiently high energy threshold for the detector, so as to accept only elastic events), comparison of the count rates with and without the spherical shell yields the nonelastic cross section. While simple in principle, such experiments require great attention to details and corrections for finite-geometry effects such as multiple scattering, and sensitivity to the detector threshold. The large error bars and the scatter in the existing measurements attest to the difficulty of carrying out sphere-transmission experiments reliably.

A particularly well documented set of measurements was performed at Livermore in the late 1950's (Refs. [4],[8],[9],[10]), in which the necessary corrections were carefully considered. Their data at 14 MeV are shown in Fig. 4 for a wide variety of nuclei across the periodic table. The scatter in the data appear to be consistent with the claimed uncertainties and a fairly smooth behavior of the nonelastic cross section with Z, which builds confidence in the accuracy of these data. These results have been heavily relied upon in evaluations at Livermore and in the determination of optical potentials such as that of Ref. [5]. In the present context, we take these results as evidence that the sphere-transmission technique can yield accurate results when carried out with sufficient attention to detail.

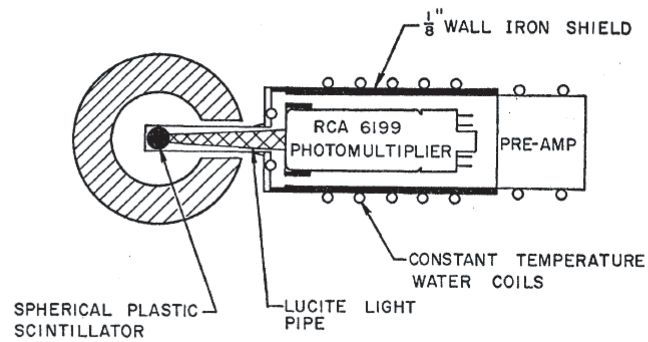

FIG. 3: Typical setup for a sphere-transmission experiment, from Ref. [8]. A parallel neutron beam incident from the left fully illuminates the sphere.

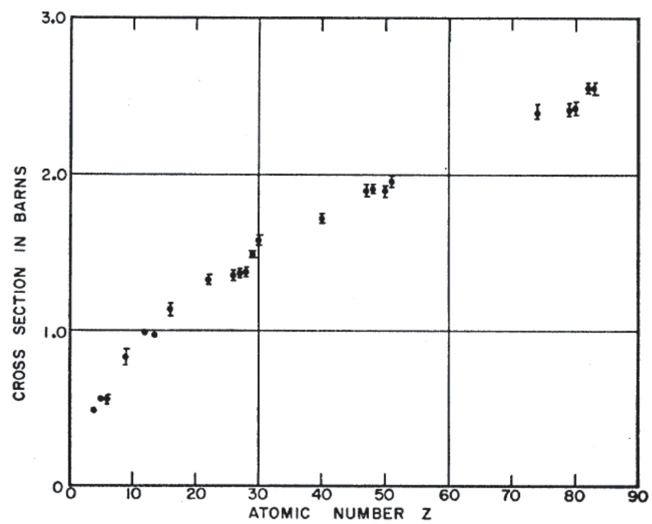

FIG. 4: Measurements at 14.2 MeV of the compound formation cross section by the sphere-transmission technique, as reported in Ref. [10].

III. MODIFIED SUBTRACTION METHOD

In searching for an alternative method for determining the nonelastic cross section, it is tempting to consider the direct subtraction of the angle-integrated elastic scattering from the total cross section,

$$\sigma_{reac} = \sigma_{tot} - \sigma_{elas}, \tag{1}$$

where the nonelastic cross section is designated by σ_{reac}. However, this is subject to large errors arising from the subtraction of two numbers, and is also particularly dependent on the reliability of the systematic error estimates in two experiments of very different type. By using the definition of Wick's limit, it is possible to circumvent these problems in favorable cases by inducing correlations between the two terms in the subtraction expression. We briefly describe this technique, which has been developed and applied to ^{208}Pb, ^{54,56}Fe, ^{232}Th, and ^{238}U in Refs. [11],[12],[13].

We define σ_0^W, the Wick's limit value for the c.m. zero-degree differential elastic cross section, and η, the fractional deviation of the true zero-degree cross section σ_0 from its Wick's limit value by

$$\sigma_0^W = \left(\frac{k}{4\pi}\sigma_{tot}\right)^2 \quad \text{and} \quad \eta = \frac{\sigma_0 - \sigma_0^W}{\sigma_0^W}. \tag{2}$$

We also define a quantity

$$F = \frac{\sigma_{elas}}{\sigma_0} = \frac{1}{\sigma_0}\int d\Omega \frac{d\sigma_{elas}}{d\Omega}, \tag{3}$$

which is determined entirely by experiment. Using these definitions for η and F we can rewrite Eq. 1 as

$$\sigma_{reac} = \sigma_{tot} - (1+\eta)F\left(\frac{k}{4\pi}\right)^2 \sigma_{tot}^2, \tag{4}$$

which expresses the nonelastic cross section in terms of three independent quantities, σ_{tot}, η, and F. The fractional uncertainties due to uncertainties in these quantities, which are to be added in quadrature, are

$$\frac{\Delta\sigma_{reac}^{(1)}}{\sigma_{reac}} = \left|2 - \frac{\sigma_{tot}}{\sigma_{reac}}\right| \frac{\Delta\sigma_{tot}}{\sigma_{tot}}, \tag{5}$$

$$\frac{\Delta\sigma_{reac}^{(2)}}{\sigma_{reac}} = \left(\frac{\sigma_{tot}}{\sigma_{reac}} - 1\right)\frac{\eta}{1+\eta}\frac{\Delta\eta}{\eta}, \tag{6}$$

$$\frac{\Delta\sigma_{reac}^{(3)}}{\sigma_{reac}} = \left(\frac{\sigma_{tot}}{\sigma_{reac}} - 1\right)\frac{\Delta F}{F}. \tag{7}$$

In the energy range of interest here, the nonelastic cross section is approximately equal to the nuclear area, and the total cross section oscillates with energy about twice this value. Thus the quantity between straight brackets in Eq. 5 is typically very small, and can even be zero at specific energies; the sensitivity to errors in σ_{tot} is consequently very weak. A similar argument indicates that the expressions in parentheses in Eqs. 6 and 7 are approximately unity. The dependence on η, which is calculated from an optical model, introduces a model dependence which has been studied in [11] and shown to be very weak over a wide range of target masses and energies. In this method the largest uncertainty typically comes from the factor F, which is computed from experimental elastic scattering angular distributions by Legendre-polynomial fitting to extrapolate to zero degrees and to determine the angle-integrated elastic cross section. Sufficiently accurate extrapolation to zero degrees requires angular distributions with many angular points and with a rather small minimum angle (≈10–15 degrees).

Results for ^{54,56}Fe are shown in the upper portion of Fig. 5, together with measurements from the CSISRS

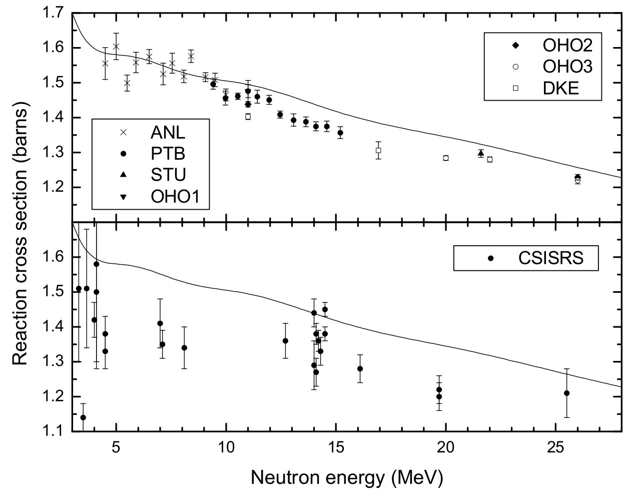

FIG. 5: Top: Nonelastic cross sections for ^{54,56}Fe using the modified subtraction technique; angular distributions used to calculate the F factor are identified in Ref. [12]. Bottom: Nonelastic cross sections for these nuclei from CSISRS database. Solid curves represent the global optical potential of Koning and Delaroche [14].

database in the lower portion. Both are compared with the predictions of the Koning-Delaroche global optical potential [14]. The results from the modified subtraction technique exhibit smaller errors than those from CSISRS, and the cross sections are significantly larger. We note that there is good agreement between the new results near 14 MeV and those from the Livermore sphere transmission measurements [8]. There also appears to be rather good consistency between the results using F factors calculated with angular distributions from different laboratories. The new results appear to provide an improved basis for comparison with optical-model predictions, and we see that the Koning-Delaroche potential predicts cross sections that are too high by about 4% over most of the energy range above ≈10 MeV.

The modified subtraction technique has also been extended to deformed nuclei. The analysis is more complicated than for spherical targets because the angular distribution measurements normally include the strongly-excited members of the ground-state band as well as the elastic scattering from the ground state. Corrections for the effects of these unresolved inelastic excitations are made using coupled-channels calculations, and are believed not to introduce significant additional uncertainty. Compound-nuclear formation cross sections have been calculated using angular distributions in the range 4.5–10 MeV measured in 0.5-MeV steps at Argonne National Laboratory on ^{232}Th and ^{238}U [15]. The results are shown in Fig. 6 along with the previous measurements and optical calculations for ^{238}U. Since the cross sections are expected to be only very weakly mass dependent (roughly as $A^{2/3}$), we have plotted the results for ^{232}Th (open squares) and ^{238}U (filled squares) on the

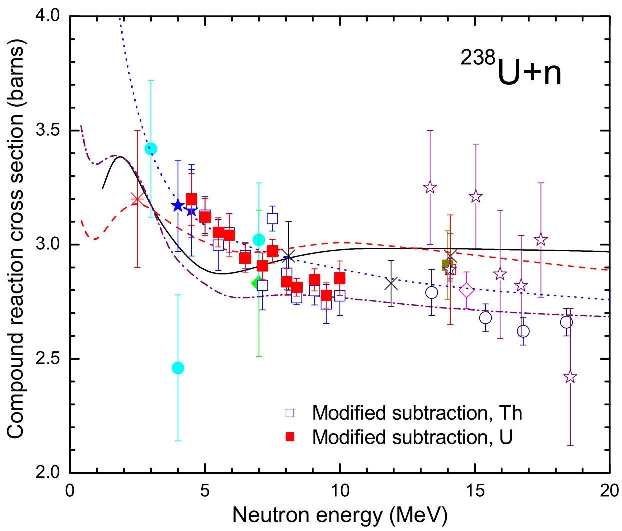

FIG. 6: Cross sections in the range 4.5–10 MeV from the modified subtraction technique for ^{232}Th (open squares) and ^{238}U (filled squares) added to the results shown in Fig. 2.

same graph. The results for the two targets appear consistent, and they indicate a rather well-determined monotonic decrease with energy that was not evident in the previously available data. However, this energy dependence is not in good agreement with any of the three optical potentials shown.

IV. SUMMARY AND RECOMMENDATIONS

We have shown that nonelastic cross sections are rather poorly determined experimentally, and that optical potentials are sufficiently variable in their predictions that they are not an adequate substitute for accurately measured data. We have pointed out some of the difficulties in making direct measurements using the principal technique (spherical-shell transmission) and noted one data set that we believe shows that this technique can yield accurate results. We have described a new technique (modified subtraction) that appears to yield good results, but in at least one case (the actinides) the discrepancy in energy dependence with several optical potentials is not understood.

To make progress, we suggest that new sphere-transmission experiments should be made on a limited set of nuclei, both spherical and deformed. Advances in detector simulation and electronics capabilities since most of the measurements were made should enable a careful assessment of the accuracy of the technique. Such new measurements can also be used to validate the modified subtraction technique.

Acknowledgments

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